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Ocean fertilization using deep ocean water (DOW)

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Abstract

Food production in the world is likely to become an urgent subject needing to be solved in the near future due to the steady increase of the world human population and the deterioration of farm lands for agriculture in the most productive areas. A large stock of nutrients in deep ocean water (DOW), below the euphotic zone of the world ocean, has great potential for enhancing existing marine production which could subsidize the production of animal protein on land. Three trials of ocean fertilization currently being carried out in Japan to increase fish and other marine products are summarized as follows: mixing more nutrient-rich bottom water with nutrient-poor shallow water by means of an artificial seamount and prevailing current actions on the continental shelf; adding more nutrient-rich deep ocean water (DOW) to nutrient-poor surface water after it has been heated from passing it through electric power plants as a coolant; and directly discharging more nutrient-rich DOW to nutrient-poor shallow euphotic water as density current after mixing it with warm surface water.

Key Words: *deep ocean water, DOW, ocean fertilization, seamount, primary production, phytoplankton, fish production, continental shelf, open ocean, nutrients, density current*

1. Introduction

Food security has always been one of the most important subjects for human society. The "Green Revolution", which greatly contributed to enhancing agricultural production in the world over the last 50 years, is now facing deteriorating farm lands due to over-use of fertilizers and agricultural chemicals. No new useful crop strains have been developed over the last few decades. These factors make it difficult for any further increases in food production, or to even maintain the existing level of food production. Fisheries catches, which support the human food supply mainly as animal protein, are also decreasing because of over-fishing and environmental deterioration of fish habitats through various human activities (Takahashi, 2000).

Among the biological communities in this biosphere, the coral reef community is known to have the highest level of primary production, and average production of a coral reef is as high as 4000 g dry-weight.m^{-2}.$year^{-1}$ of organic matter (Whittaker and Likens, 1975). However average production in other marine communities is about 1/10 of the coral community, or even lower such as: 500 g dry-weight.m^{-2}.$year^{-1}$ for upwelling regions; 360 g dry-weight.m^{-2}.$year^{-1}$ for continental shelf waters; and 125 g dry-weight.m^{-2}.$year^{-1}$ for pelagic oceans. These low levels of production in marine environments are mainly a result of limited nutrient availability in the euphotic zone, where primary producers such as phytoplankton carry out photosynthetic production.

Primary production in most of the ocean is ex-

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pected to be enhanced if nutrient availability for primary producers can be improved. There is no question that primary production can be stimulated by adding limiting nutrients to a given euphotic water body, whether they are enclosed in experimental culture flasks, or are mesocosm containers having a volume such as 1 to over 1000 tons (Bienfang, 1970: Ishizaka *et al.* 1983; Takahashi *et al.*, 1982). There have also been several trials to improve actual nutrient environments for natural algal communities by bringing up subsurface water containing more nutrients into nutrient-poor euphotic zones (Roels *et al.*, 1971; Roels, 1980; North, 1977, 1987). Gundersen and Bienfang (1970) suggested using cold deep ocean water (DOW) for cooling electric power plants followed by the use of the heated nutrient-rich DOW for ocean fertilization. The Fisheries Agency of Japan enacted the "Organic Law of Fisheries" in 2001, to strongly stimulate efforts to maintain existing stocks of fish and other fishing targets; and to increase future stocks around the exclusive economic zone (EEZ) of the Japanese islands. Ocean fertilization is one of the possibilities to meet those goals.

Direct ocean fertilization using DOW was tested experimentally in Toyama Bay in the summer of 1989 and 1990. Twenty-six thousand tons of DOW was pumped up from 220 m and spread across the surface after being mixed with two parts of surface water. Various baseline data were obtained from the experiment (Nakata *et al.*, 1991; Iseki *et al.*, 1994). Fertilization effects of DOW were recognized by the recovery of a seaweed community along the flow of DOW that was discharged from the Kochi Deep Seawater Research Laboratory (Watanabe *et al.*, 2000; Hayashi *et al.*, 2003). Due to low concentrations of nutrients even in the DOW, a huge amount of DOW was required as well as a large amount of energy for pumping. Thus, natural energy, such as ocean thermal energy conversion (OTEC), was suggested as a way to meet pumping and other energy requirements in the open ocean (Otsuka, 1997). A relatively large-scale ocean fertilization project, in a warm offshore ocean, has been proposed to create a large new fishing area (Takahashi *et al.*, 1993; Matsuda *et al.*, 1999; Matsuda *et al.*, 2002).

Three research programs testing ocean fertilization using the nutrients contained in DOW have been carried out in Japan. The first is an experimental evaluation of primary production stimulated by nutrients brought up by an artificial seamount designed to enhance turbulent mixing. The second is an evaluation of primary production stimulated in coastal waters using nutrients in heated DOW after it passed through a power generation plant. The third is an experimental evaluation of stimulating surface primary production by directly spreading DOW pumped up into the euphotic zone in the open ocean. Construction of artificial seamounts is restricted to continental shelves shallower than 200 m because of increased economic and engineering difficulties at greater depths. The use of DOW as power plant effluent is also restricted to near shore areas, as well as being restricted to obtain DOW. The direct use of DOW of the third type has no major limitations by depth and distance from shore but there are other additional requirements such as a strong structure that can stand in open ocean conditions, a structure large enough to have a positive effect, securing a suitable energy supply and so on. Each experiment mentioned above involves several new technological developments. These include efficient pumping of near bottom water to the euphotic zone using a combination of artificial seamounts and current actions, pumping up DOW from a depth of a few 100 m and keeping it within the euphotic zone by controlling its temperature by passing it through cooling thermal plants, or diluting it with warm surface water to minimize diffusion for at least a few days.

2. Background concept for ocean fertilization

Marine production, including that of fish and sea mammals, depends entirely on primary production by photosynthetic organisms (Ryther, 1969). It is therefore essential to increase primary production in order to enhance marine production. Primary production in the ocean is mainly controlled by available solar radiation or nutrient supply. As solar radiation is unamenable to control by human efforts, nutrient supply is the target to increase marine primary production (Takahashi, 2000).

In the ocean, all nutrients acting as bio-elements generally increase in concentration with depth, tend to reach a maximum concentration around 1000 m, and remain at high concentrations almost down to the bottom (Sverdrup *et al.*, 1942). This nutrient accumulation in the subsurface water is due to decomposition of organic matter by heterotrophic organisms. Thus, oceanic primary production will be enhanced if nutrients in DOW can be supplied to the euphotic zone, where photosynthesis is carried out. Energy required to raise DOW to the sea surface using a mechanical method, such as pumping, is equivalent to 1/1000 of energy for heating DOW so that the specific gravity of DOW equates with that of surface water (Isaacs and Schmitt, 1969).

Among about 30 bio-elements required by phytoplankton, the macro-elements nitrogen, phosphorus and silica and the microelement iron are apt to be in insufficient supply in the euphotic zone of the ocean. An unbalanced supply of nutrients, such as one low for silica but high in other elements, discourages the growth of diatoms, so a phytoplankton community poor in diatoms develops. Similar species changes also occur due to changes in nutrient concentrations even with a balanced composition: lower concentrations encourage small phytoplankton whereas larger cells are stimulated at higher nutrient fluxes. Dominance of large diatom species supports a classical straight food chain contributing to fisheries organisms. However, dominance of small phytoplankton species does not give much enhancement effect to fisheries organisms but it enhances others.

Furthermore, it takes at least one or more days to promote phytoplankton growth by changing nutrient environments using quick dilution, then certain levels of nutrient concentrations have to be maintained for a certain time period to initiate phytoplankton growth. Due to its high density, DOW pumped into the euphotic zone will tend to sink below the euphotic zone before the nutrients in it are taken up by primary producers. To achieve effective ocean fertilization, it is necessary to prevent sinking and rapid dilution of DOW in the euphotic zone. Thus, adjustment of DOW buoyancy by heating it with the waste heat of a power generation plant, mixing of DOW with surface water, or physical confinement of discharged water or some other means is required.

Nitrate is one of the essential nitrogenous nutrients that are in limited supply in the ocean. The total amount of nitrate in DOW would be as much as 600×10^9 tons N, which is more than 6000 years worth of nitrogenous nutrients currently used in agricultural activities around the

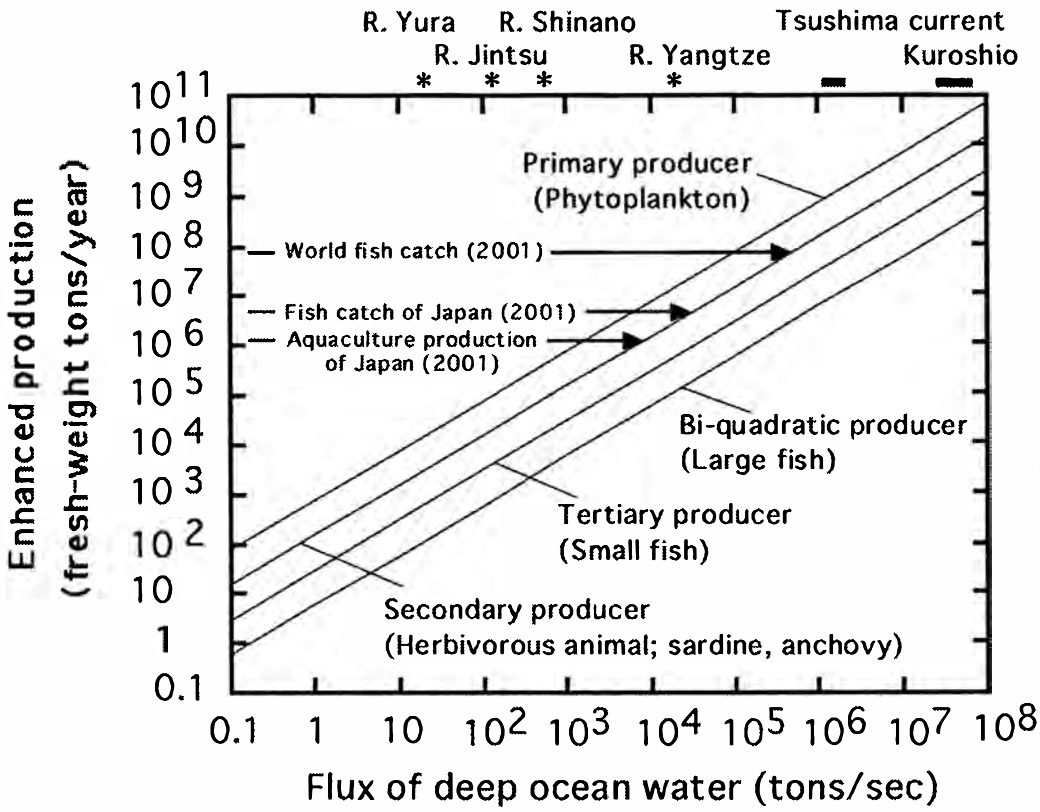

Figure 1. An estimation of enhancement of primary, secondary, tertiary, and bi-quadratic production using deep ocean water (Iseki, 2000). (The original figure was redrawn for the English version based upon the assumptions mentioned in this text).

world. This is based on the assumption of 30 μM as the average nitrate concentration of DOW below 200 m in the entire world ocean and 95 % for DOW percentage in the total seawater. The amount of phosphorus nutrients in DOW is in even greater amounts for agricultural use than nitrogen.

Under natural conditions, subsurface nutrient rich water comes up to the surface very slowly in most sea areas but at rather rapidly in a few limited cases such as upwelling and during seasonal vertical water mixing. In the former case, frequent nutrient supplies stimulate primary production, which result in greater fish production, and support robust fisheries (Ryther 1969).

Iseki (2000) predicted possible fertilization effects using DOW under the following assumptions: (1) DOW contains 30 μM of nitrate and other bioelements in balanced concentrations; (2) the nitrogen to carbon atomic ratio of phytoplankton using nitrate is 16:106; (3) the conversion factor for organically combined carbon to organic matter production by phytoplankton is two and that for dry-weight to fresh-weight is five; and (4) the ecological efficiency for material and energy transfer between each trophic level throughout the food chain is 20 %.

As shown in Figure 1, the upwelling rate of DOW at 0.1 – 1 ton.s^{-1} (about 10^4 to 10^5 tons per day) could produce several 100 to 1000 fresh-weight tons per year of primary production which could support several 10 to 100 fresh-weight tons per year of secondary production by planktivores such as sardines, anchovies and so on. To increase secondary production to be as large as the yearly fish catch of Japan (5×10^6 fresh-weight tons in 2001), about 10^5 ton.s^{-1} (10^{10} tons per day) of DOW is required. To reach the level of the world fish catch in 2001, the amount of DOW required is in the order of about 10^6

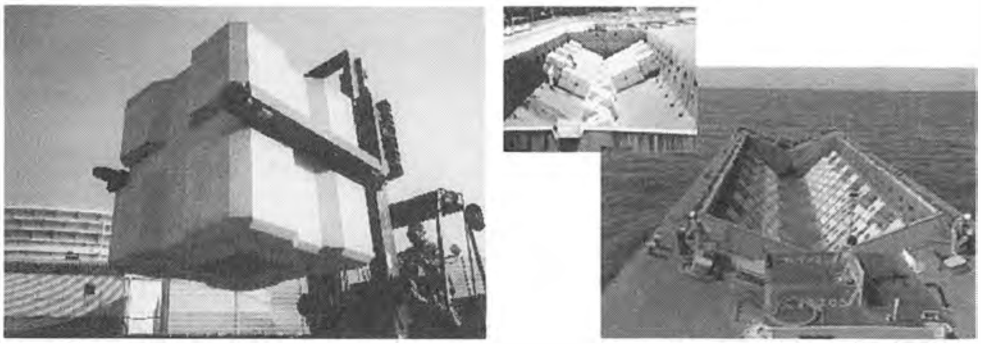

Figure 2. "Ashcrete" blocks (made from flyash cement) used to construct underwater seamount: a (left). an Ashcrete block; b (right). delivery of Ashcrete blocks from a bottom-opening barge at sea (Suzuki, 2000).

ton.s^{-1} (10^{11} tons per day) for planktivores.

Ocean fertilization using subsurface nutrient-rich water could be achieved anywhere in the ocean. However, areas cannot be expected to achieve effective fertilization where subsurface water has low levels of nutrients and are subject to extensive and frequent vertical water mixing (due to low water column stability).

3. Experimental approaches to ocean fertilization

3.1. Artificial seamount

On continental shelves shallower than about 200 m, bottom water contains more nutrients than the shallower water. Surface primary production could therefore be enhanced if bottom water is mixed with nutrient-poor shallow water by tidal or other currents. To increase fish and fisheries organisms on the continental shelf, some enhancement to primary productivity can be made possible by supplying nutrients from the bottom water to the euphotic zone. An underwater, dual-cone seamount has been proposed as an effective way to achieve water mixing between the bottom and the shallow layers (Suzuki, 1995). According to flume experiments, the most effective form of the conical seamount was a peak height of 30 m and the width of 400 ~ 600 m for 100 m water depth. In the area of 100 m water depth, the total volume of each seamount was 330×10^3 m^3. Concrete blocks approximately 1.6 m each side (4.1 m^3 in volume, about 7 - 8 tons in weight) was proposed as a basic unit to construct a twin-cone type seamount (Figure 2a). Concrete blocks were delivered to the sea floor by free falling from a bottom-opening barge (Figure 2b). Since the location of each block on the sea floor varies according to the prevailing direction and speed of the current during its free fall, the delivery point of the blocks from the barge is controlled under consideration of the current conditions. In flume experiments of 1/100 in scale, the loss rate of blocks due to dispersion and burial was less than 30 % during the random free fall operation. Since there is some free space around blocks (total free space is about 50 % of the seamount), total volume of blocks required to construct one twin-cone seamount with a cone height of 30 m and radius of 120 m is about 210×10^3 m^3. The transverse direction of the ridge between the dual cone seamount was set at the sea floor to cut across the prevailing current in the area to achieve the most effective mixing of bottom water with shallow water.

Because of the large amount of material required to make concrete blocks to construct an artificial seamount, it is essential to obtain suit-

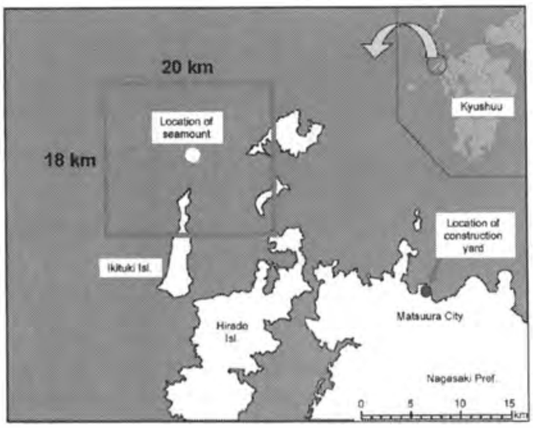

Figure 3. Map of the construction site for the underwater seamount off Ikituki Island, Nagasaki Prefecture (Suzuki, 2000).

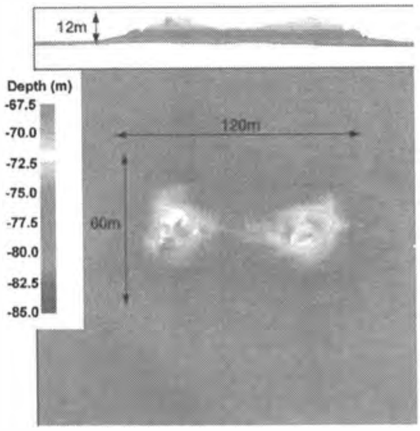

Figure 4. Shape of the underwater seamount constructed off Ikituki Island, Nagasaki Prefecture. Seamount structure was determined using the underwater depth sounding (Suzuki, 2000).

able materials that are cheap, bulky, plentiful, do not cause environmental destruction by damaging hills or beaches, and cause no major environmental deterioration of seawater by leaking heavy metals and other hazardous chemicals. Flyash produced from electric power plants using coal was therefore chosen as the material for making the concrete blocks (Suzuki, 1999). Despite increases in flyash production, no demand for practical usage has developed, and as matters stand, almost all extra flyash tends to be dumped into shallow coastal waters in reclamation projects.

Flyash concrete blocks having a unidirectional pressure strength of more than 1.96×10^5 Nmm^{-3} was advanced under the following production conditions (by weight): 65 % flyash, 11 % cement, 23 % water, and 1 % mixing agent (Suzuki, 2000). Sonication treatment was used to mix the contents, which saved the quantity of both water and cement used in the normal procedure; and resulted in a shorter incubation period, no adhesion of the concrete mixture to the mold, and no cracking. Concrete blocks made of flyash are called "Ashcrete" blocks. The specific gravity of Ashcrete blocks varied from 1.7 to 1.9 depending upon the quality of flyash used, which is lighter than an ordinary concrete block of 2.3. Since the light-weight Ashcrete blocks do not sink easily into muddy bottoms, they are suitable for constructing underwater seamount on muddy or sandy sea floors. Furthermore, a steady increase in strength of Ashcrete blocks in seawater with time is another advantage. Safety for various marine organisms due to possible leaching of chemicals from Ashcrete blocks and the succession of living colonies on the blocks have been assessed (Marino Forum 21, 1989; Collins *et al.*, 1992).

A seamount was experimentally constructed at a depth of 84 m on the continental shelf off Nagasaki Prefecture as shown in Figure 3. This was a research and development project (1995-2000) of the Marino Forum 21, which was supported by the Fisheries Agency of Japan (Suzuki and Takahashi, 1997; Suzuki, 2000). About 5000 Ashcrete blocks were set over 3 years (1997-1999), until a twin-cone seamount with a peak height of about 12 m, width of 120 m and a side width of 60 m was constructed (Figure 4). A simulation model predicted that strong upwelling would result from a reciprocal tidal current across the seamount (Suzuki 1995, Honda, 2000). During the course of construc-

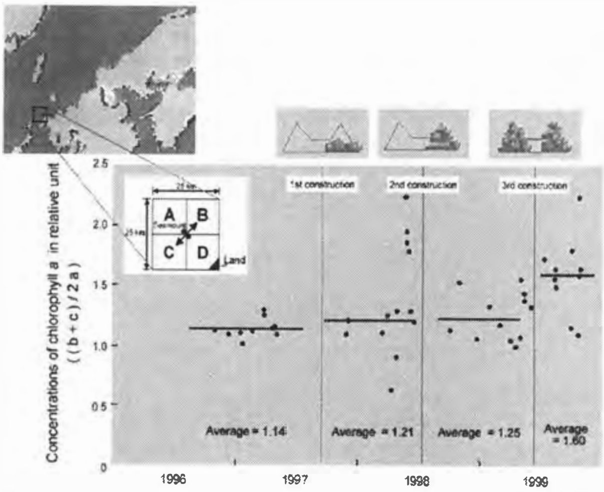

Figure 5. Changes in chlorophyll concentrations detected by satellites around the seamount during construction. The areal mean of the chlorophyll concentration (b+c) for section B and C was normalized using data for the offshore reference Section A(a). The arrows crossing the seamount indicate the direction of the tidal current around the seamount. The relative average chlorophyll concentration ((b+c)/2a) shown by horizontal bars increased by about 1.4 times when 75 % of the seamount had been completed (compared to the condition without seamount) (Kumagai *et al.*, 2000).

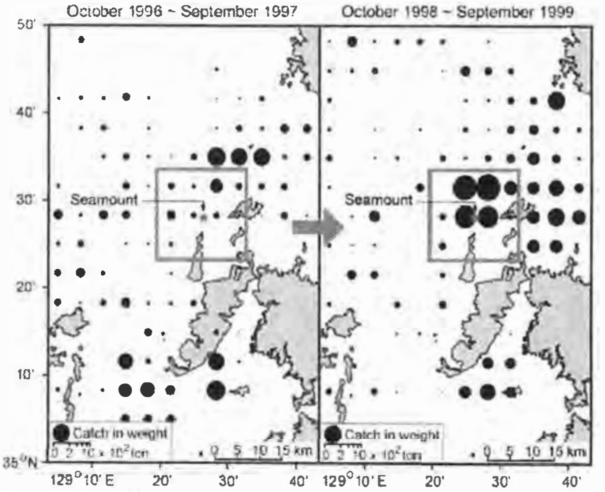

Figure 6. Changes in fish catches caught with purse-seine nets before and after constructing the seamount. Fish-catch records were compared before and after the construction within the area of 18 × 20 km around the seamount (Tomoda and Nishimura, 2000).

tion, chlorophyll concentrations in the surrounding area of the seamount, detected by satellites, showed a steady increase by about 1.4 times the average when 75 % of the seamount was completed (Figure 5) (Kumagai *et al.*, 2000). Fishing operations also showed an obvious increase of fish catch in the area (Figure 6) (Tomoda and Nishimura, 2000). Fresh-weight fish catch in the area of 18 km × 20 km around the seamount (under construction) increased from 250 tons (mostly saurel) in 1996/97 to 1500 tons (mostly anchovy) in 1998/99. A large number of fish schools were actually recognized by direct observations of a Remotely Operated Vehicle (ROV) elsewhere around the seamount. They were composed various species of juveniles and adult fishes including many commercially valuable fishes.

ROV observations also showed various species of organisms attaching to the surface of Ashcrete blocks, which created a rich rock ecosystem within a year after setting the blocks. The surrounding seafloor of the seamount is entirely covered by soft mud, but a different rock ecosystem was obviously formed from the placement of the blocks. Since the top of seamount was still way below the euphotic zone, no photosynthetic organisms could live autotrophically on the seamount.

There are three possible effects from constructing underwater seamounts to enhance ocean fertilization and increase fisheries organisms of as follows. The first is the stimulation of primary production by nutrients being brought up from the bottom water and mixed with the euphotic zone water. The second is the formation of a rock ecosystem by placing Ashcrete blocks on the seafloor, as these blocks supply a substrate for various species of sessile organisms that live mostly on particles sinking from the water above. The third is the seamount creates an attractive environment for fishes and other organisms.

Once a seamount is constructed, it will last almost forever with little maintenance effort. Such seamounts will be suitable for areas shallower than 100 m or so, and most effective if there is a strong prevailing current, particularly in warm seasons. Even though nutrient concentrations near the bottom in the area suitable for seamounts may not be high, useful ocean fertilization effects can be expected. Generally, deeper depths give greater fertilization effects. However, as depth increases, the size of a seamount will become huge; and there will be a great increase in the total materials required for construction in deeper sea areas. This will result in a greater engineering and economic difficulties. Based upon the success of the ocean fertilization project mentioned above, the Fisheries Agency of Japan has designated seamount construction as one of the promising ocean fertilization programs, and provides constant financial support for their construction.

3.2. Direct use of heated DOW passed through electric power plants

Since DOW tends to sink below the euphotic zone because of its low temperature when it is discharged directly into the ocean surface layer, except in extremely shallow water of 10 m or so, preheating of DOW by passing it through an electric power plant for cooling has been proposed (Isaacs and Schmitt, 1969; Bienfang, 1970; Gundersen and Bienfang, 1970). The use of DOW for cooling power plants can have several advantages, such as: an increase in cooling efficiency by the low temperature of DOW; no biofouling within the entire cooling system without special measures; and almost no entrainment of organisms causing system damage. Additional construction costs to extend the intake water pipe to depths deep enough to collect cooling water is required, which would be the only major disadvantage, but one easily offset by the benefits mentioned above. Furthermore, since heated DOW does not sink to great depths, it can fertilize the ocean if it is kept within the euphotic zone by controlling its temperature. Considering that the total amount of seawater currently used for cooling power plants in Japan is as large as approximately 10^4 ton.s^{-1}, if DOW is used as coolant it could support slightly less than the current level of annual aquaculture production in Japan (see Figure 1).

A research and development project for the use of DOW as cooling water for power plants has been carried out as one of the national research programs on "Research and development on the effective use of energy and resources of deep ocean water (1999–2003)" by the Japan Ocean Industries Association (JOIA) under the supervision of the New Energy and Industrial Technology Development Organization (NEDO) with financial support from the Ministry of Economy, Trade and Industry (METI). In the project, 1×10^6 ton.day^{-1} (ca. 10 ton.s^{-1}) of DOW was assumed to be pumped up for cooling a 600 MWe thermal fossil-fuel plant (Kadoyu *et al.*, 2003), and the heated DOW effluent was used in a trial of coastal water fertilization.

The practicality and possibility of using DOW as a thermal plant coolant was evaluated in the project and the necessary technologies needing to be developed was assessed. An existing power plant, designed to use surface seawater as a coolant, showed an increased efficiency of 3.5 % in northern and central Japan in summer by using DOW. Furthermore, the heat transfer area requirement of a steam condenser can be considerably reduced with the use of DOW for optimally designed power plants, together with some improvements in plant efficiency (Kadoyu *et al.*, 2003). This benefit can be applied to power plants constructed in the future. There was only a small amount of entrainment of

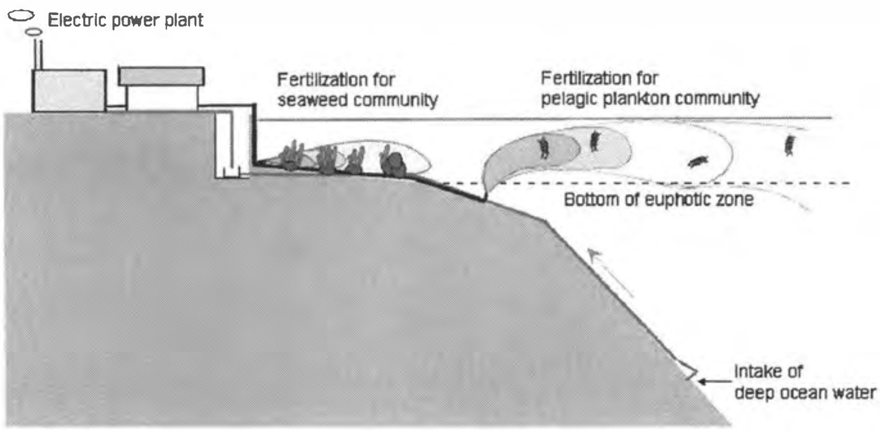

Figure 7. Schematic diagram showing the potential for ocean fertilization of near-shore seaweed community and pelagic plankton community using DOW heated by passing it through an electric thermal plant (Hayashi *et al.*, 2003).

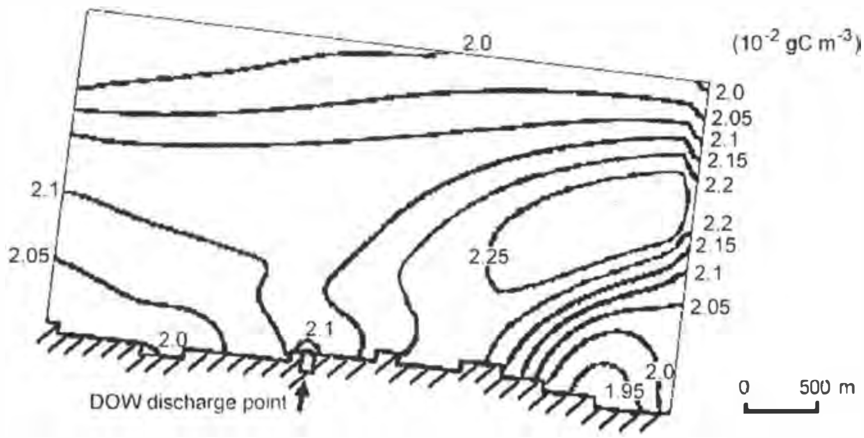

Figure 8. A model estimate of ocean fertilization increasing phytoplankton production as shown by an increase in phytoplankton biomass in g C.m^{-3} due to heated DOW of 10^6 ton • day^{-1} discharged into coastal water (Hayashi *et al.*, unpublished data).

organisms living around the intake mouth of DOW in Namerikawa, Toyama, where the intake inlet was a few meters above the bottom at 310 m (Hayashi *et al.*, 2003). No observable bio-fouling has been noticed in the Kochi Deep Seawater Research Laboratory where DOW has been pumped up continuously since 1989 from 310 m using 12.5 cm reinforced polyethylene pipe. Similar results with no major bio-fouling have also reported from the Natural Energy Laboratory of Hawaii over a much longer time period. They have been pumping DOW from below 600 m for nearly 20 years.

Considering that most power plants are located close to coastal waters, heated DOW can be delivered from land to almost any location in coastal waters. As shown schematically in Figure 7, a seaweed community will be fertilized if DOW is discharged into a rocky shore area within the euphotic zone, whereas a pelagic plankton community will be fertilized if heated DOW is discharged further offshore. A possible enhancement to primary production was estimated using a numerical simulation model in the project mentioned above. The simulation showed an obvious increase in primary production in the offshore water (Figure 8).

Although the use of heated DOW for ocean fertilization is still being evaluated, it is worth considering it for both cooling and ocean fertilization in the future. Because heating is essential to reduce the specific gravity of DOW, it is quite important to adjust the buoyancy of DOW by heating it by passing through cooling systems. Cooling is not only for electric power plants but also for several other possibilities such as air conditioning.

3.3. Direct ocean fertilization using DOW

The Marino Forum 21 awarded research and development funds for five years from the Fisheries Agency of Japan for the direct use of DOW for ocean fertilization (2000–2004).

For ocean fertilization using DOW, at least two important challenges have to be solved: one is how to pump up a large quantity of DOW, and the other is how to keep the DOW in position within the euphotic zone with minimum diffusion, at least for a few days after discharge. Achieving ocean fertilization at an oceanic scale may require DOW containing 30 μM nitrate in the order of 1×10^6 tons per day or more in open water. Natural energy such as OTEC, solar and wind would be ideal for pumping DOW up in the sea. In the course of the Marino Forum project, OTEC was suggested as the most promising energy source for pumping DOW up in comparison with wind, photo-voltatic, waves, shore-based electric power and diesel fuel (Ouchi *et al.*, 2002; Watanabe *et al.*, 2003).

There was a pioneer experiment for ocean fertilization carried out in Toyama Bay in 1989 and 1990, which was supported by the Special Coordination Fund for Promoting Science and Technology of the Science and Technology Agency of Japan. In that project, DOW was sprayed onto the sea surface from a floating barge named "Hoyo", which pumped DOW up from 220 m. Although the buoyancy of DOW was adjusted by mixing it with two parts surface water, the floating of DOW within the euphotic zone was not confirmed, possibly due to limited amounts of DOW being discharged and it behaving unexpectedly. In the Marino Forum project, a density current generator was applied to discharge and plunge DOW horizontally into a certain layer of the euphotic zone in a stratified water column. The aim was to minimize sinking and diffusion of DOW after discharge into the euphotic zone (Ouchi *et al.*, 1998). To avert DOW from sinking below the euphotic zone, it was mixed with two parts of warm surface water and discharged as a density current.

The Marino Forum project decided on Sagami Bay, near Tokyo, as the experimental field site because a large counterclockwise eddy often develops and circulates at the surface there, possibly due to effects of the Kursoshio current (Figure 9). If the DOW discharged from the discharger became trapped within an eddy, the diffusion of nutrients in DOW was expected to slow down. In the final design, 1×10^5 tons of DOW from a 200 m depth was pumped up per day by the revolving power of an impeller with a 2.35 m diameter (lower impeller) through a steel riser pipe with an internal diameter of 100 cm and a wall thickness of 31 mm. One part of the DOW was mixed with two parts of warm water collected from a depth of five meters to reduce the specific gravity of DOW (Figure 10) (Ouchi *et al.*, 2003). The water from the five-meter depth was taken in using the same revolving impeller action (upper impeller). The mixture of DOW with five-meter water was then discharged slowly at 20 m as a density current. The DOW discharger, named "Takumi", was operated continuously with the use of energy generated by a diesel engine (to evaluate the potential for fertilizing Sagami Bay). "Takumi" was set at the site at the end of May 2003, and discharged DOW since the end of July 2003.

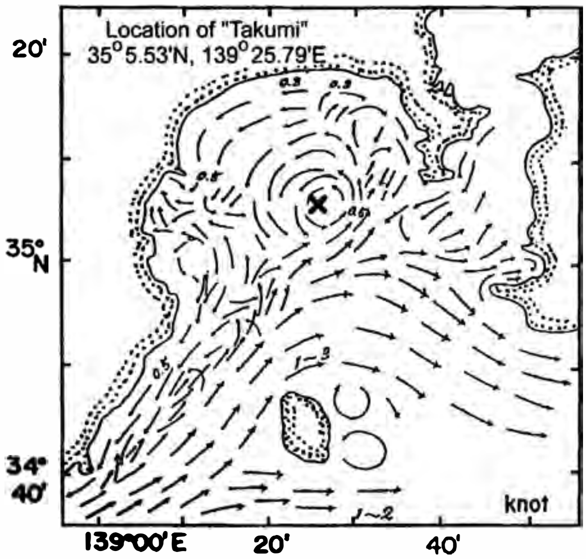

Figure 9. Counterclockwise surface eddy frequently observed in Sagami Bay. DOW discharger "Takumi" (location shown by the "X" symbol) was set near the center of the eddy (Iwata and Matsuyama, 1989).

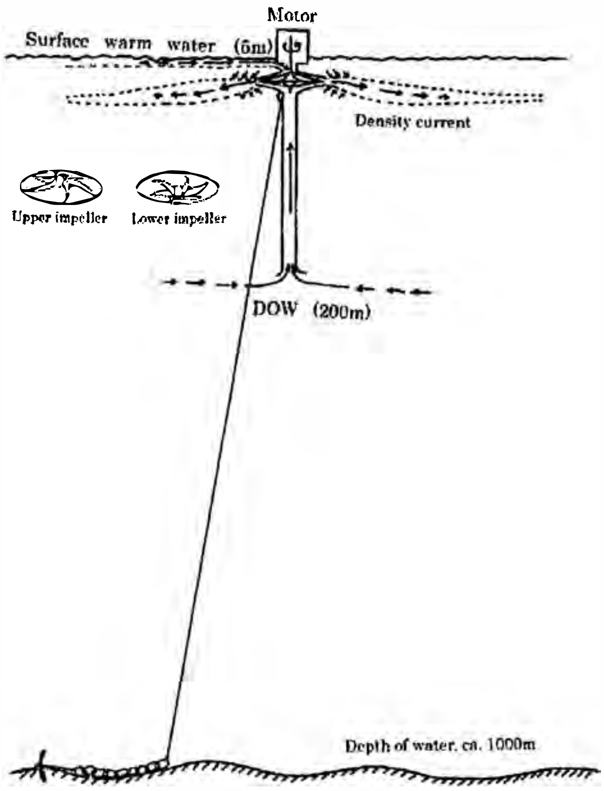

Figure 10. Conceptual design of the offshore-based DOW discharger "Takumi" (after Ouchi *et al.*, 2003).

DOW containing about 20 μM of nitrate at 10 °C was pumped up, mixed with the five-meter water containing less than 1 μM nitrate at about 25 °C in summer, and discharged as a density current. New technology developments include: (1) the entire design of the DOW discharger "Takumi", which stands for year-round operation in the open sea; (2) practical and economical installation of a riser-pipe and floating offshore structure; and (3) technology for detecting ocean fertilization.

4. Future perspectives

Utilization of DOW containing rich nutrients from nearly 100 m or more in depth to fertilize a large volume of the ocean has now been tested. Several essential engineering technologies have been developed as a necessity. Three experiments undertaken in Japan have been reviewed in this paper. Improvements in the technologies are still need for efficient and practical application, although most of the technologies required for constructing underwater seamounts have reached the level of practical application. Some technologies associated with the two other approaches have to be improved before practical operation can be achieved.

Within the three, ocean fertilization experiments reviewed here, each has at least site-specific advantages. Seamounts will be suitable for fertilizing shallow waters of continental shelf areas such as those less than 100 m with low or moderate concentrations of nutrients at the sea bottom. DOW effluent from power plants containing rich nutrients and heated up will be an ideal source for ocean fertilization but is restricted to near shore waters with a steep coastal slope where it is not suitable to construct a seamount. DOW can be pumped up at any location where it is relatively easy to pump DOW from below approximately 200 m. This generally requires a huge and strong structure to overcome rapid diffusion of nutrients by supplying great amounts of DOW and to be able to stand in the rough environment of the open ocean. Therefore, direct pumping of DOW for fertilization will cover most deep-water areas that are not suitable for the other two approaches.

To utilize DOW for ocean fertilization, there must be many ways to do it, including those introduced in this paper. Those methods will depend upon specifics of the local planning site, and the actual combination of other uses for deep water (in addition to fertilization). Combining the use of DOW for ocean fertilization and as a coolant will be ideal for the efficient utilization of the cold energy and nutrients of DOW, where it is possible. Direct pumping of DOW in the open ocean can be combined with several other purposes such as electric power generation, extracting metals in DOW, and so on.

CO_2 uptake during photosynthetic production using nutrients contained in DOW also requires attention. Since the CO_2 concentration in DOW is already higher than the surface water, we have to consider the balance of how much CO_2 is fixed compared to CO_2 released into the air. Considering that the average age of DOW is around 100 years at 300 m around Japan, the equilibrium of CO_2 between the air and the surface seawater was much smaller compared to the present age because of low CO_2 concentrations in the air at that time. Therefore, more CO_2 could be absorbed up to reaching the new equilibrium point when DOW is used for ocean fertilization.

Since the utilization of DOW is an imposition of new human activity on the ocean, we must be careful not to significantly disturb the ocean system. One of the important issues is to find out what level of DOW usage will not to disturb the ocean system. Otsuka (2002) estimated a level based upon the magnitude of temporal variation in ocean currents and suggested using a given limit of DOW resources that is within natural fluctuation levels, because nature can already cope with such fluctuations.

The rich silicate in DOW could specifically enhance diatom growth, but stimulation of other species such as those causing red tides has to be checked carefully. To avoid such a problem, DOW operations for ocean fertilization should be at, or facing, the open ocean rather than being in enclosed sea areas where red tides are apt to occur.

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海洋深層水（DOW）を用いた海域肥沃化

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要　旨

このところ確実に継続している世界の人口増加や食糧生産基地の農地の劣化を考えると，近い将来，世界の食糧生産は最重要課題の一つになりそうである．一方，水深数 10 m の真光層以深に存在する巨大な栄養塩類のストックは，現状の海洋の生産を高める一大可能性を秘めており，それが実現すれば，陸上での動物タンパク質生産を補うことが可能である．そこで魚や他の水産生物の増産を目指して，現在，日本で進められている海域生産性向上への 3 つのチャレンジを紹介する．第 1 は，大陸棚の底近くにある栄養塩類を多く含んだ海水を人工海底マウンドと流れの作用によって貧栄養の表層水と混合して肥沃化を図る．第 2 は，富栄養の海洋深層水を陸上に汲み上げ，それによって発電所を冷却し，温まった海洋深層水を浅海域に放水して藻場やプランクトン群集の生産を高める．第 3 は，大陸棚以遠の深い海域で海洋深層水を揚水し，暖かい貧栄養の表層水と混合して密度調整し，真光層中に留まるように放水することにより海域を肥沃化する．

キーワード： 海洋深層水，海域肥沃化，海底マウンド，一次生産，植物プランクトン，魚類生産，大陸棚，外洋域，栄養塩類，密度流